The January 2015 Repressurization of ISS ATCS Loop B – Analysis Limitations and Concerns

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THERMAL & FLUIDS ANALYSIS WORKSHOP
GSFC · 2015

Overview

- The problem
- What we said
- What was real
- Lessons learned

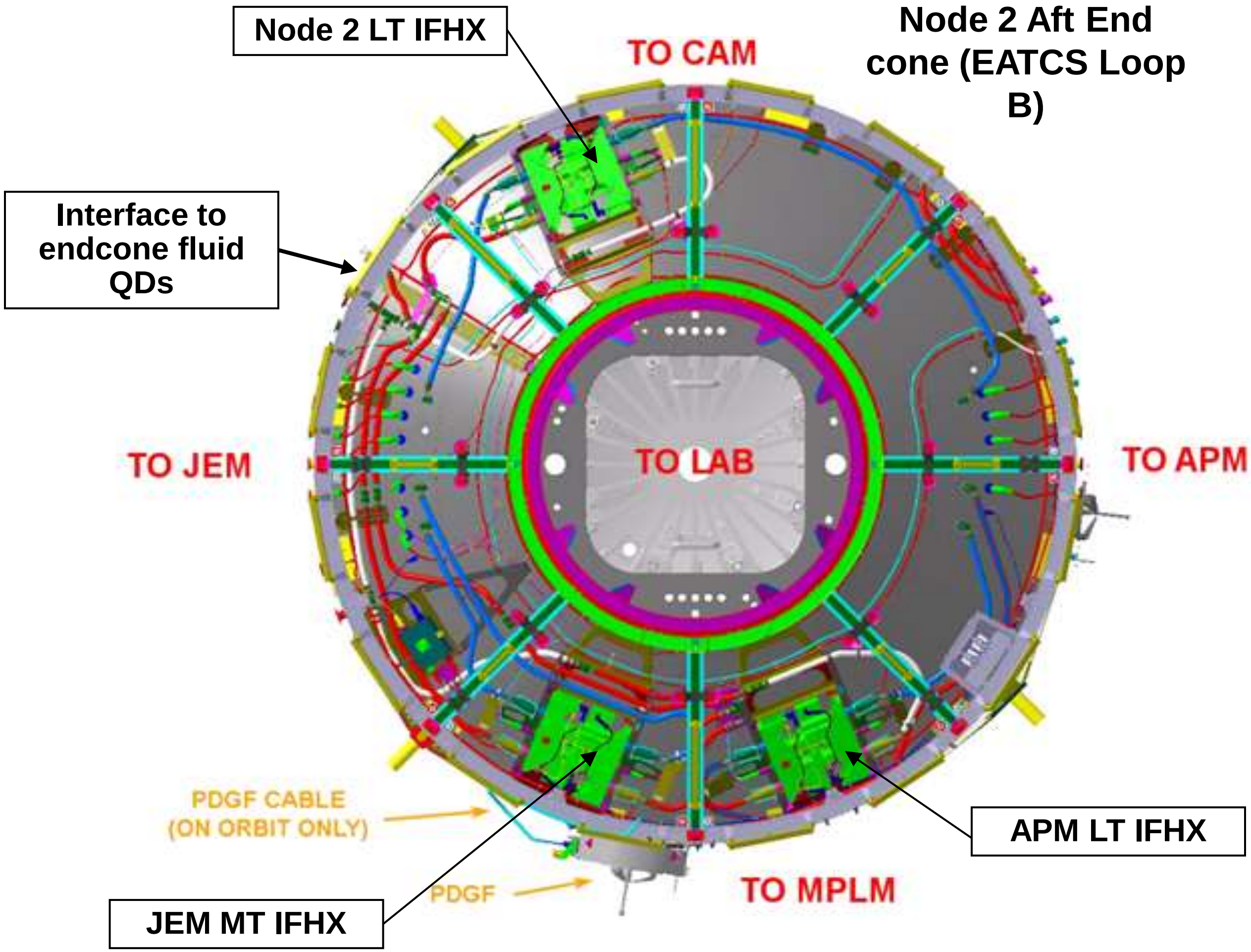
The Event

- On January 14, 2015 an ammonia alarm was sounded on the International Space Station
- Spurious accumulator level reading on the Node 2 LTL (low temperature internal water loop) accumulator indicated possible leak from external ammonia loop
- Ammonia leak protocol
  - Stop external active thermal control system (EATCS) ammonia pump
    - reduces pressure at the heat exchangers
  - Isolate ammonia tank assembly (ATA) which is used as a system accumulator
    - isolates the large (~130 kg or 300 lb) reservoir of ammonia
  - Vent nitrogen from one of the isolated radiator flow paths
  - Open system to the now-vented radiator flow path
    - creates ullage in the system
  - System becomes two-phase and will reach the saturation pressure associated with the temperature of the warmest fluid

Aftermath

- Volume calculations (the volume of the radiator passage – the pump accumulator ∆ volume) showed that 18 liters (0.64 ft^3) of ammonia vapor had been formed
  - 0.1 kg (0.21 lbm) of vapor
  - requires 120 kJ (110 BTU) of energy
    - raise 1 liter of water 28°C
  - energy is available in the fluid itself and in the lines and fittings
- Over time the fluid pressure adjusted to the highest temperature in the loop (endcone lines)
  - the liquid/vapor interface was located there
  - the local temperature set the pressure
- The pressure beat over the orbit as the average loop temperature (and average liquid density) cycled - moving the fluid between cooler and warmer parts of the endcone)
  - 905 to 950 kPa >> 21.7 to 23.3°C (71-74°F)

Node 2 Endcone Layout / IFHX Locations



Node 2 Aft End cone (EATCS Loop B)

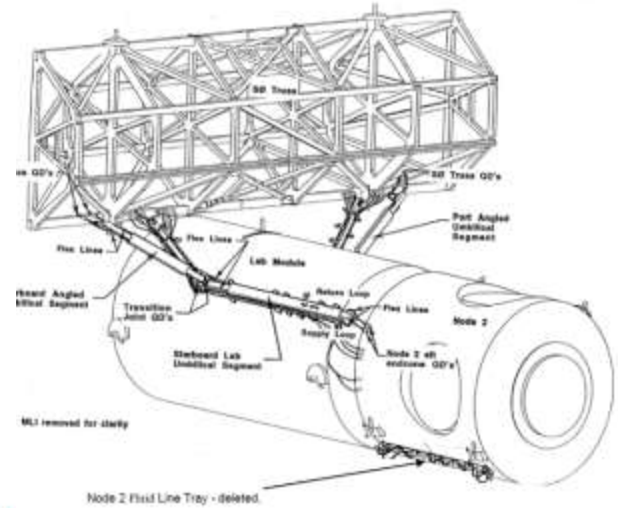
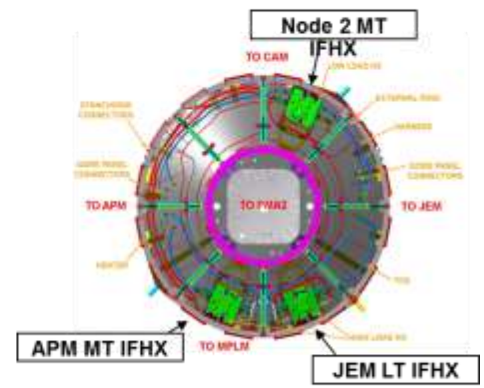
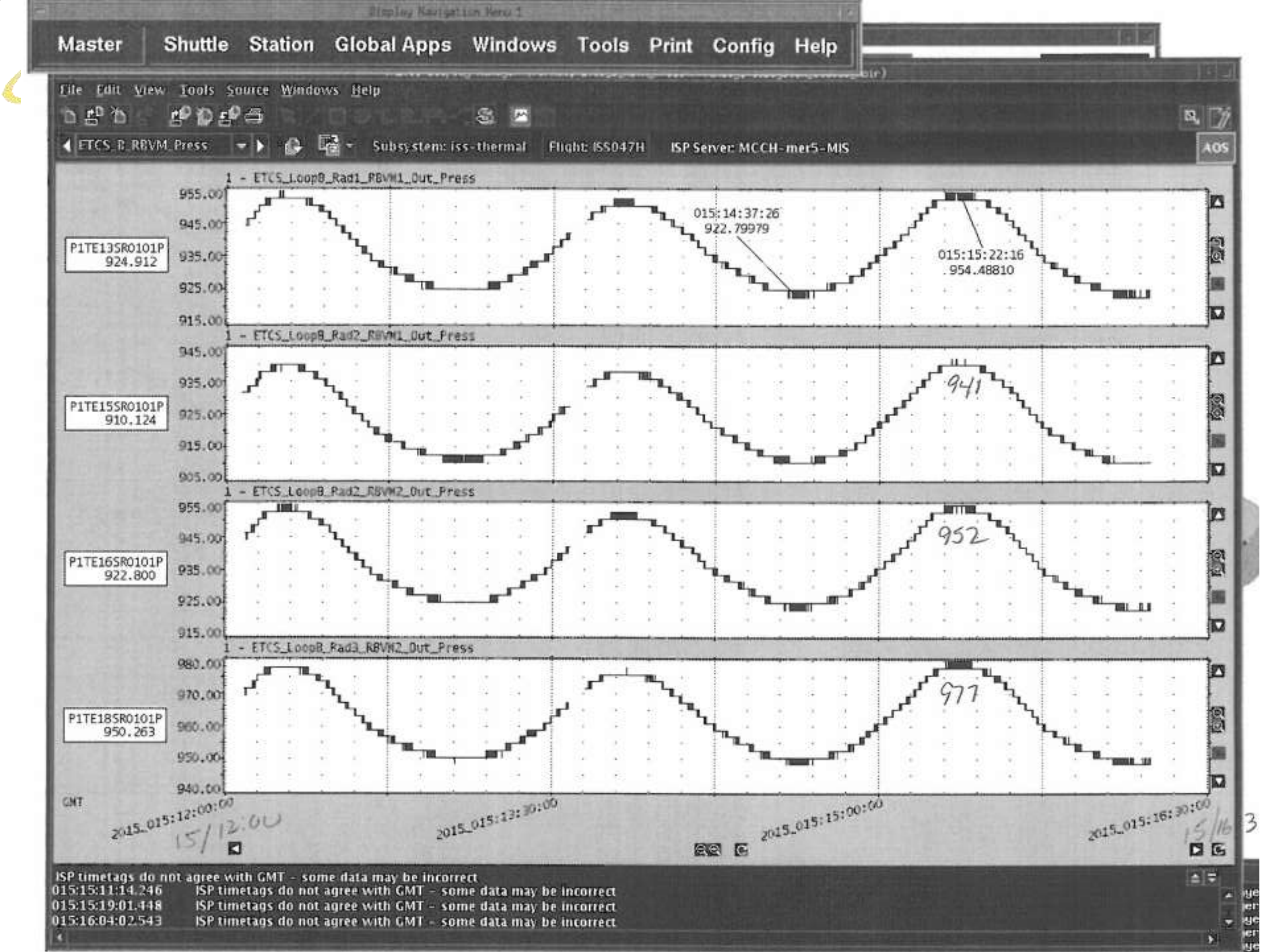


Figure 17.4-6 NH3 Umbilical Trays Deployed from S0 to Node 2



Node 2 Fwd End cone (EATCS Loop A)



Master
Shuttle
Station
Global Apps
Windows
Tools
Print
Config
Help
File Edit View Tools Source Windows Help
ETCS_B_RBVM_Press
Subsystem: iss-thermal
Flight: ISS047H
ISP Server: MCCH-mer5-MIS
AOS
1 - ETCS_LoopB_Rad1_RBVM1_Out_Press
P1TE13SR0101P
924.912
955.00
945.00
935.00
925.00
915.00
015:14:37:26
922.79979
015:15:22:16
954.48810
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915.00
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925.00
915.00
952
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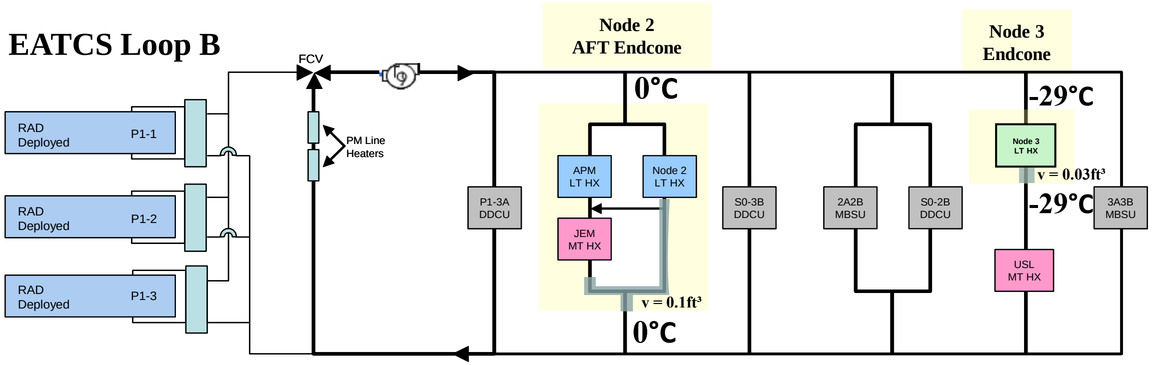
950.263
980.00
970.00
960.00
950.00
940.00
977
GMT
2015_015:12:00:00
2015_015:13:30:00
2015_015:15:00:00
2015_015:16:30:00
15/12:00
15/16
ISP timetags do not agree with GMT - some data may be incorrect
015:15:11:14.246 ISP timetags do not agree with GMT - some data may be incorrect
015:15:19:01.448 ISP timetags do not agree with GMT - some data may be incorrect
015:16:04:02.543 ISP timetags do not agree with GMT - some data may be incorrect

Recovery

- Because Loop B was stagnant, the liquid in the lines outside of the heated endcones was free to drop to the local environment temperature
- Of most concern was the boom tray temperature, which is the fluid closest to the endcones (where the heat exchangers reside)
  - during repressurization, this fluid would fill the endcones, then the heat exchangers
- Passive thermal analysis of boom tray temperatures
  - fluid upstream of Node 3 heat exchanger was -29°C (-20°F)
  - fluid upstream of Node 2 heat exchangers was 0°C (32°F)
- 18 liters (0.64 ft^3) of vapor would fill 40 m (135 ft) of 1 inch tubing
  - not enough to completely fill the endcones
  - we could not know which endcone lines were filled and which were empty

Limitations

- We did not want to send subfreezing ammonia to the heat exchangers mounted on Node 2 (Node 2 LT, JEM MT and APM LT)
  - 0°C fluid in boom trays
  - 2.8 liters (0.1 ft^3) of volume in shortest leg to Node 2 LT
  - required dwell time of four hours to increase temperature to 5.5°C 42°F (required margin)
- We did not want to send subfreezing ammonia to the Node 3 LT heat exchanger
  - -29°C (-20°F) fluid in boom trays
  - 0.8 liters (0.03 ft^3) of volume in shortest leg to Node 3 LT
  - required dwell time exceeded 12 hours to increase temperature to 5.5°C 42°F



Previous PMA Recovery Procedure

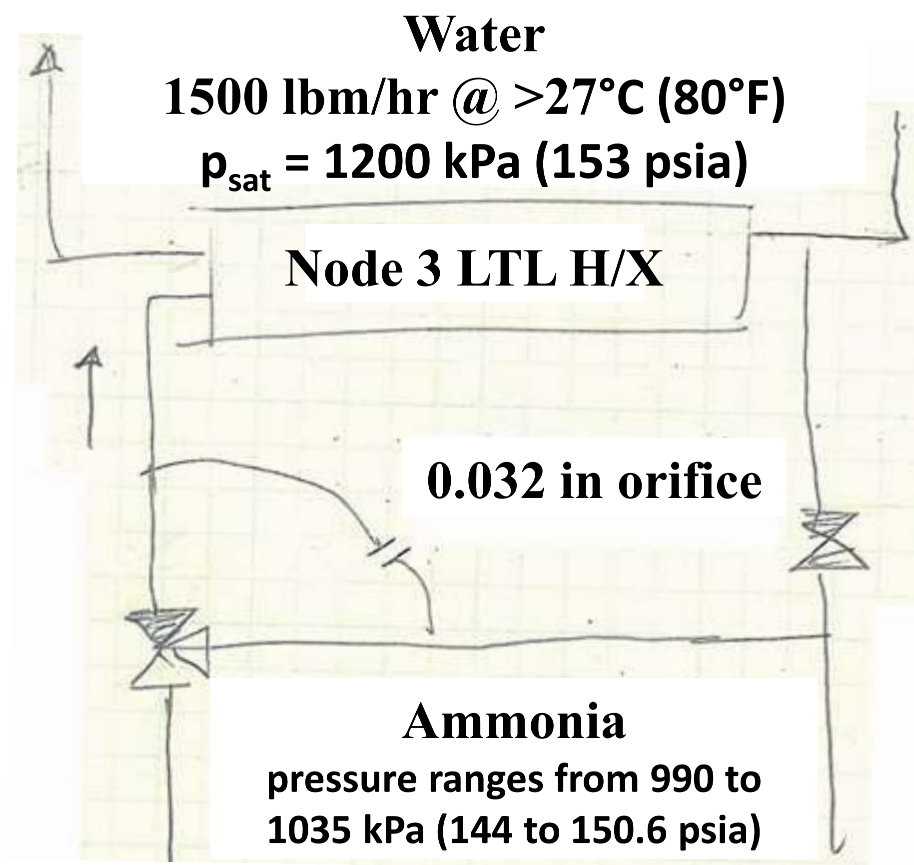
- Open ATA to system
- Pressurize enough to introduce enough liquid into system to fill the shortest leg (from boom tray to HX)
- Dwell to allow fluid to warm to endcone temperature
- Repeat

- With 0.8 liters (0.03 ft^3) critical volume and dwell time >12 hours, this would have required more than 10 days

Idea

- Could we show that freezing would not occur even if cold ammonia entered the Node 3 heat exchanger?
  - Node 3 LTL H/X was colder than the US Lab MTL H/X
- That would allow us to use
  - only the limit of the Node 2 endcone volume - 2.8 liters (0.1 ft^3)
  - a shorter dwell
    - 4 hours since the boom tray upstream of Node 2 was at 0°C

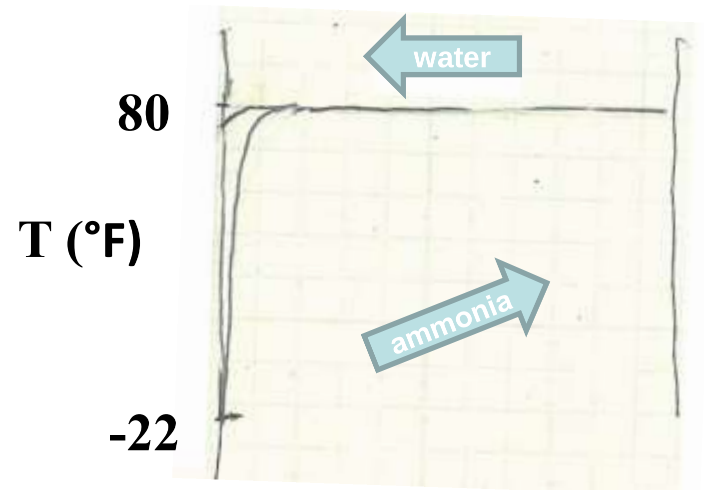
Current Configuration



-20°F
Ammonia

contemporaneous
chart

In the Heat Exchanger

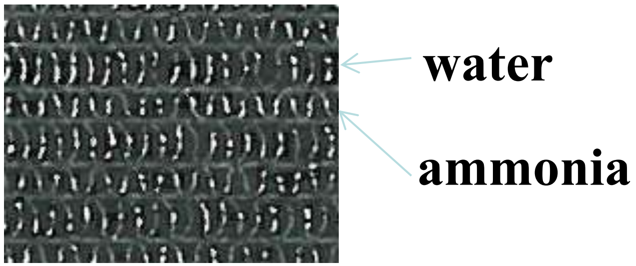


- Heat exchanger effectiveness is near unity
- When cold inflow begins, the water temperature at the exit (LHS) is 80°F
- As cold flow has passes through the core, the water exit temperature drops
- Minimum water exit temperature occurs when entire core has experienced cold flow

contemporaneous chart

At the Heat Exchanger Water Exit

- Ammonia is as cold as -20°F
- Water is colder than 80°F



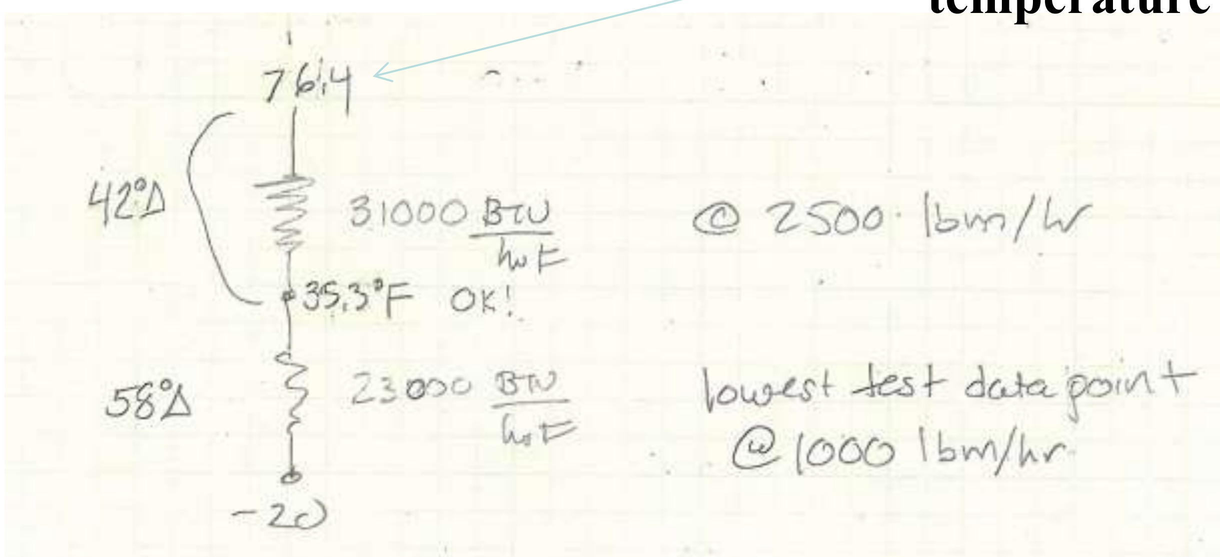
- Core metal temperature will be determined by relative magnitude of water and ammonia heat transfer
  – $UA_{water} > UA_{ammonia}$ so core temperature will be closer to the water temperature than to the ammonia temperature

contemporaneous chart

Two Results

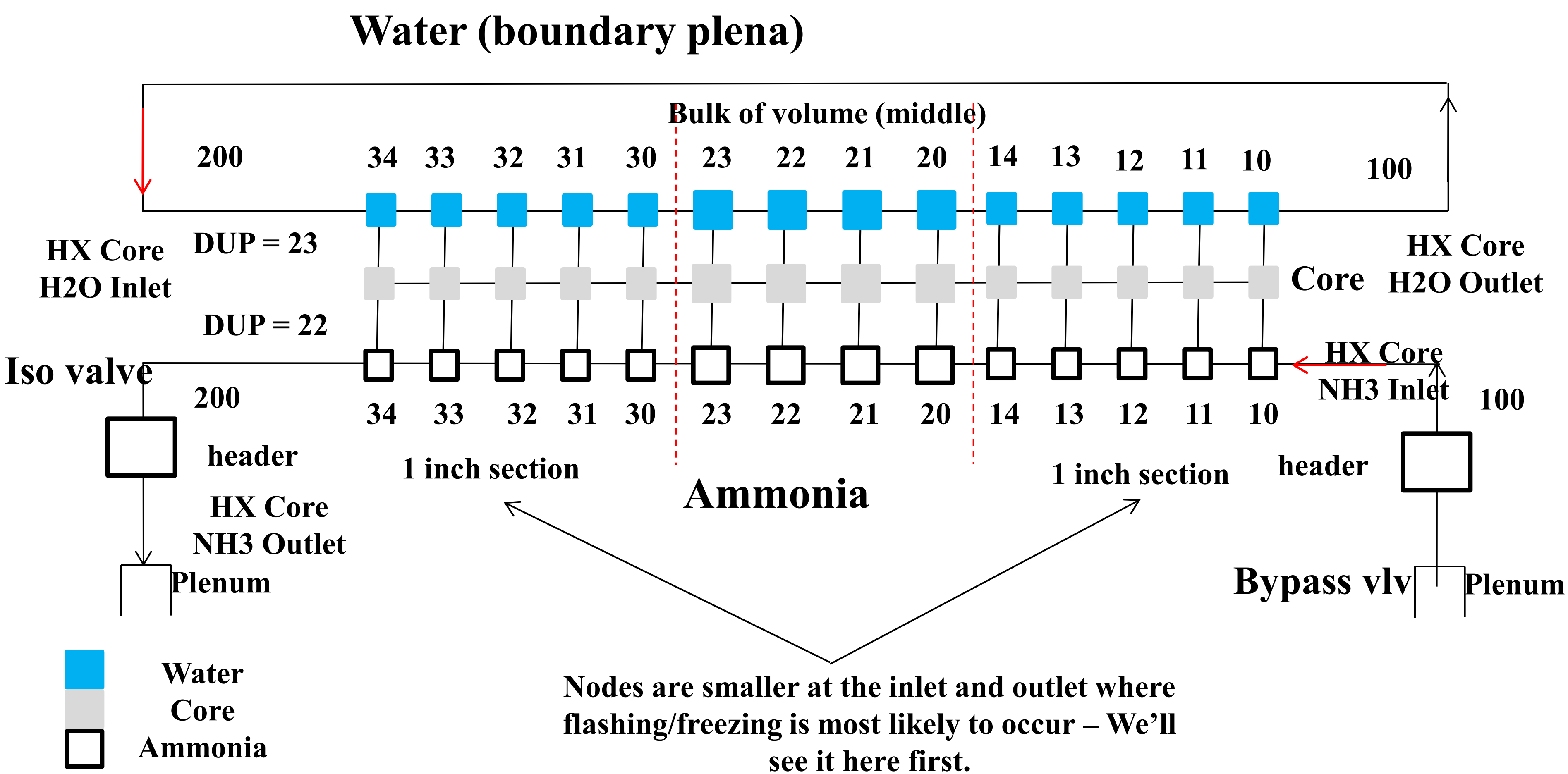
- Detailed SINDA/FLUINT model indicated that the minimum metal temperature was >15°C (60°F)
- Hand calculation

measured water temperature

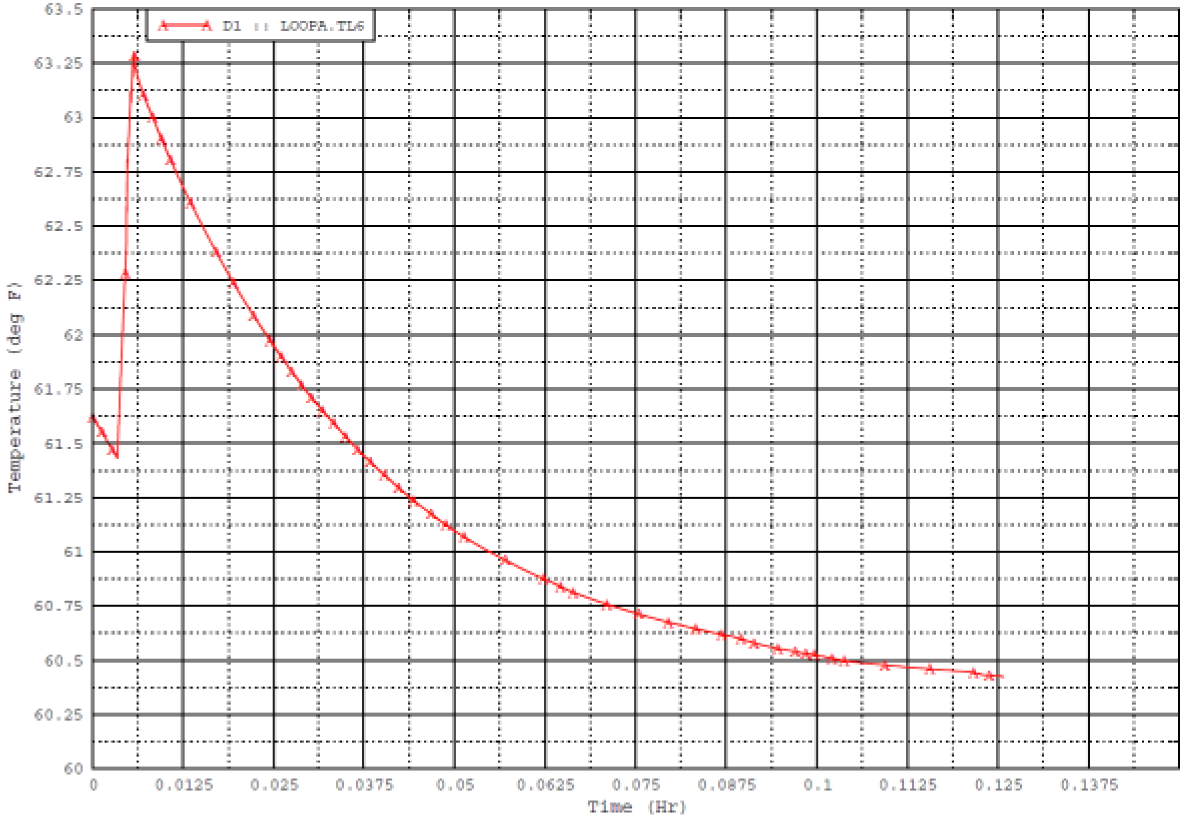


35.3°F = 1.8°C

Flowing IFHX Model Schematic Normal Operation



1st Node Metal Temperature

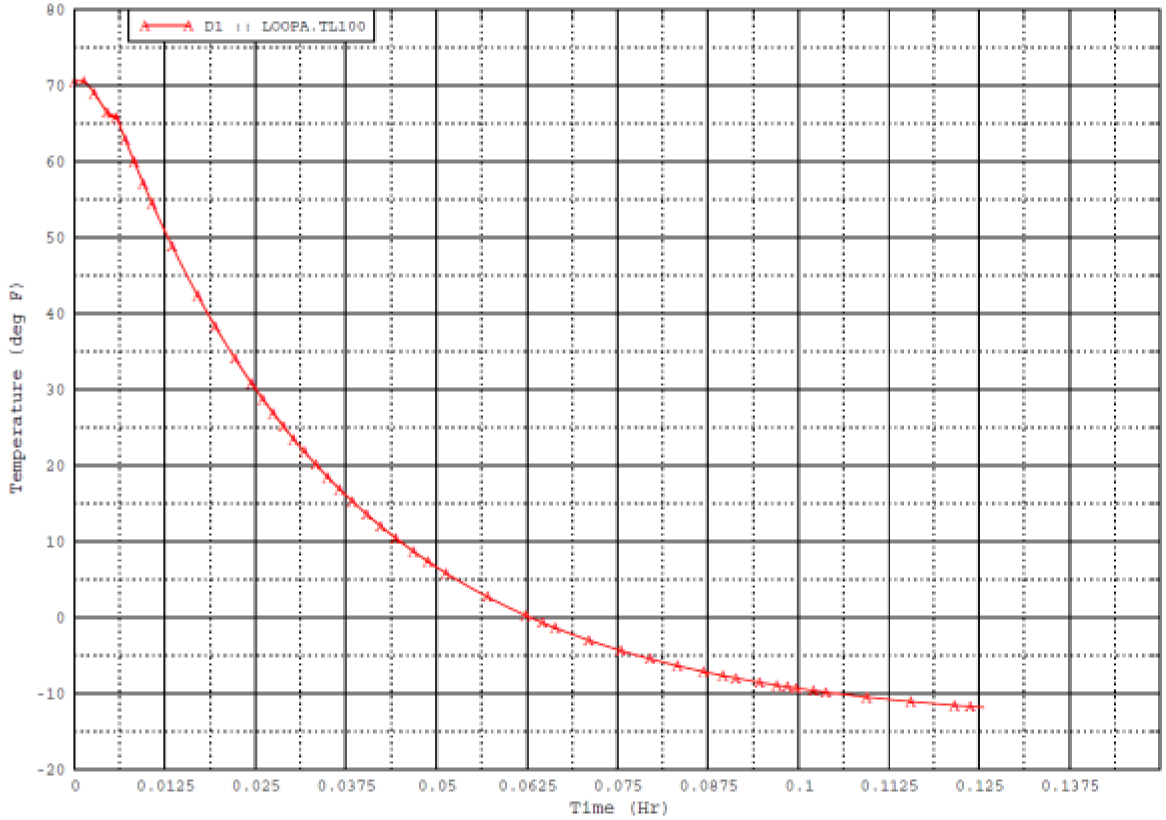


Why The Difference? (in Hindsight)

- The SINDA/FLUINT model took the heating from warm metal into account
  - ammonia was warmed to -25°C (-13°F)

  but that was not the largest effect
- The model element size was 0.2 inches
  - because the ammonia flow was so low (about 100:1 ratio), all the heat transfer took place in the first element or two
- The model was returning the <u>average</u> metal temperature within the first element, not the <u>minimum</u> temperature (which would occur at the entrance)
- We were safe to proceed despite the difference in the results because even the conservative hand calculation showed positive margin

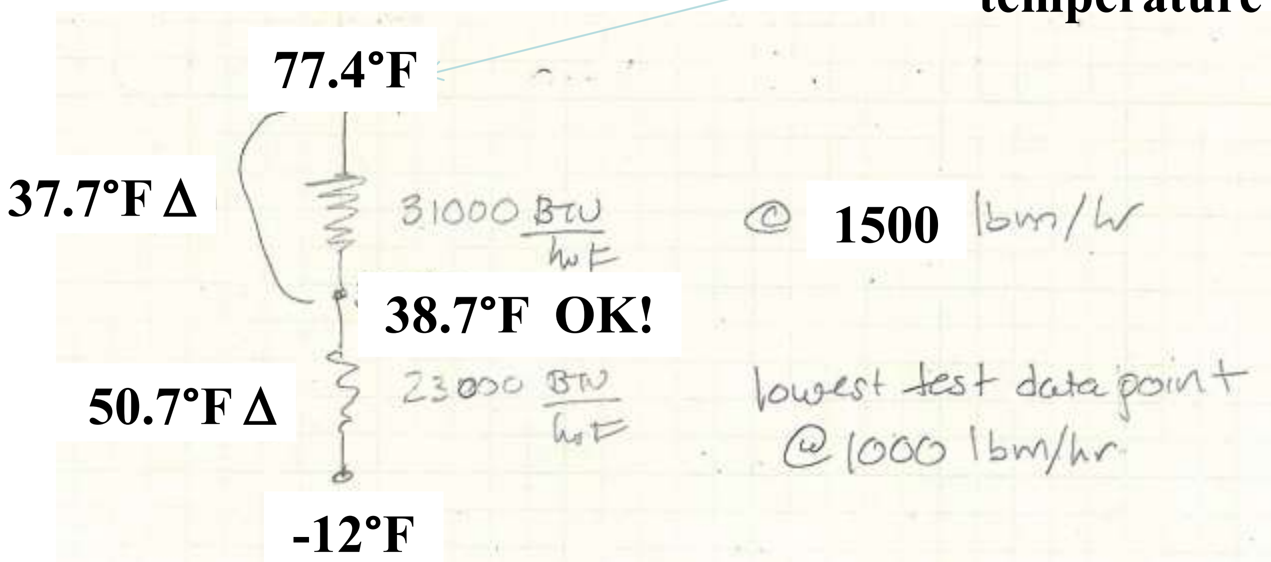
Ammonia Inlet Temperature



The Right Answer

- Hand calculation

model water exit temperature



model ammonia inlet temperature

38.7°F = 3.7°C

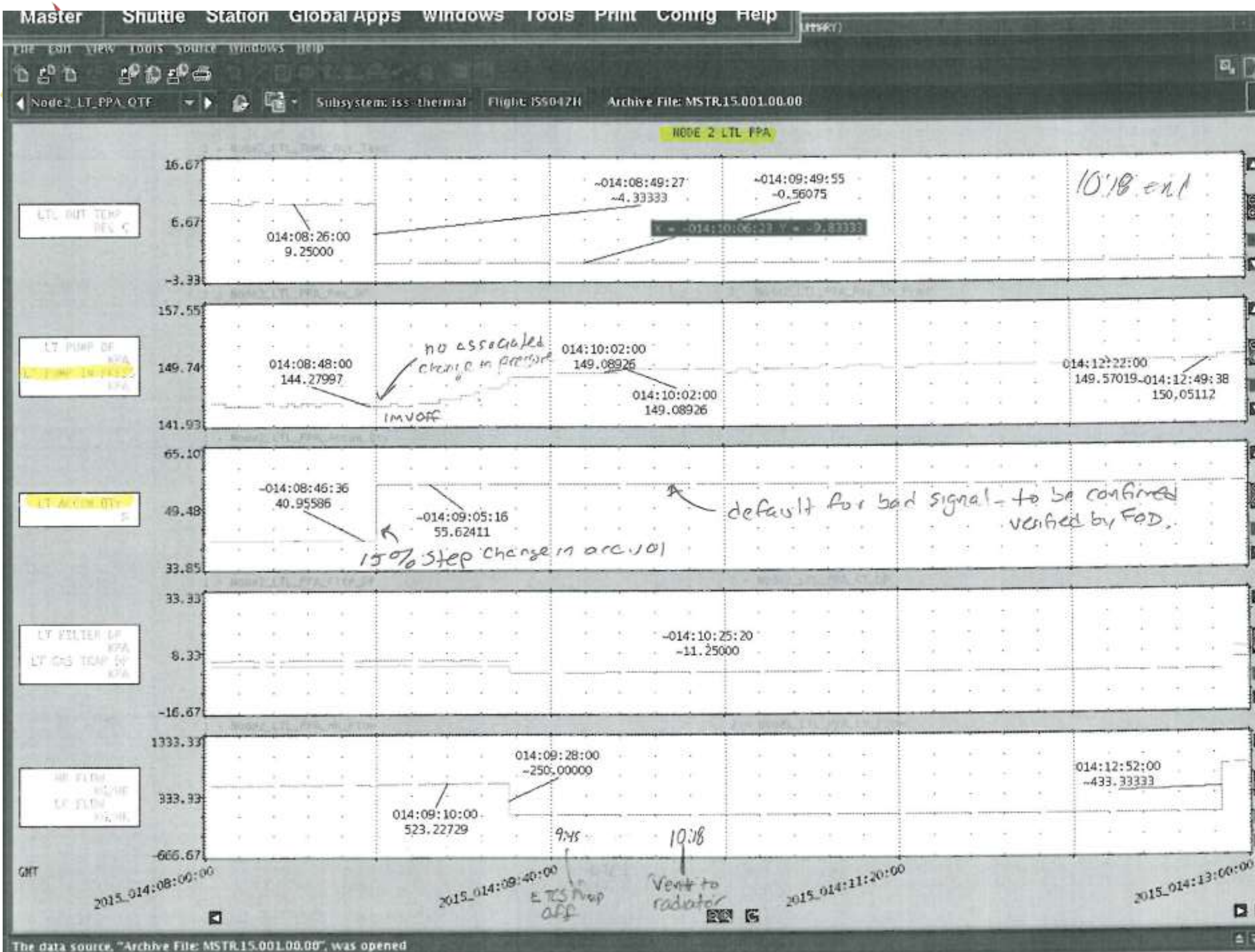
The Home Stretch

- 2.8 liter (0.1 ft^3) insertions on 4 hour centers were begun
- System hard packed after 15.7 liters (0.56 ft^3) of ammonia inserted (vs. 17.9 liter - 0.64 ft^3 initial estimate)
  - based on ATA quantity change
  - process took 24 hours
- System was ready to be restarted 4 days after ammonia alarm event

Lessons Learned

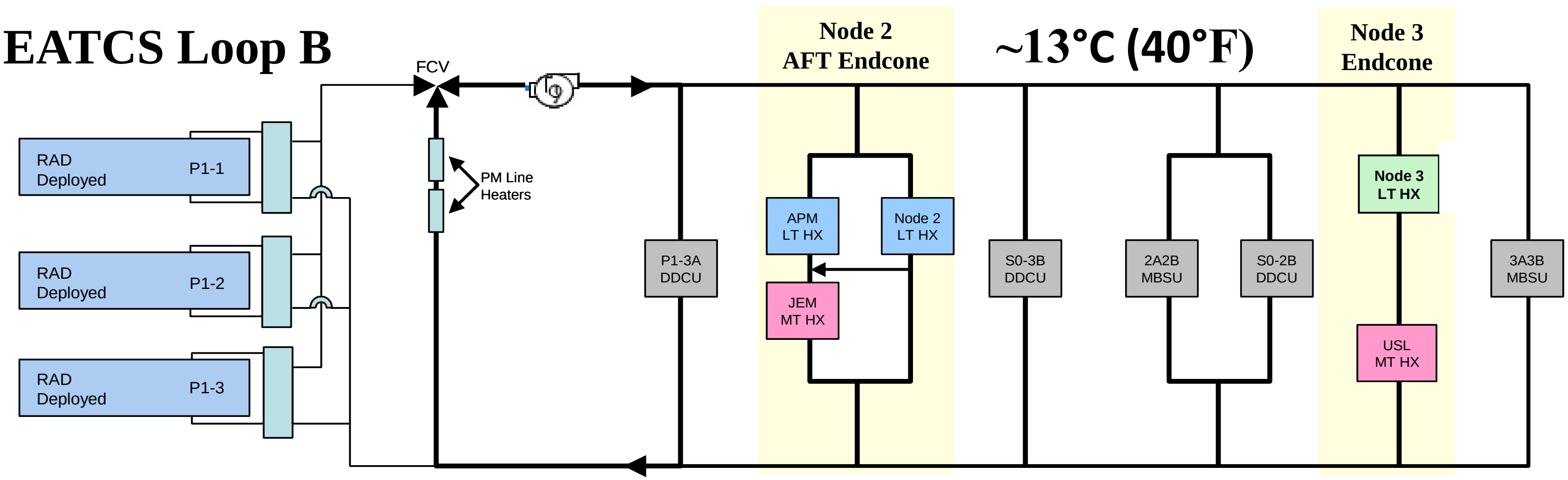
- Detailed Thermal Math Models are most accurate when they are used for the purpose for which they were developed
- Operating models outside of their planned range is risky
- Hand calculations can be used
  - as a check on the detailed model
  - to gain confidence that the chosen path is safe

Backup


Master Shuttle Station Global Apps Windows Tools Print Config Help
File Edit View Tools Source Windows Help
Node2_LT_PPA_QTF
Subsystem: iss-thermal
Flight: ISS042H
Archive File: MSTR.15.001.00.00
NODE 2 LTL PPA
16.67
6.67
-3.33
014:08:26:00
9.25000
-014:08:49:27
-4.33333
-014:09:49:55
-0.56075
10:18 end
157.55
149.74
141.93
014:08:48:00
144.27997
no associated change in pressure
IMV OFF
014:10:02:00
149.08926
014:10:02:00
149.08926
014:12:22:00
149.57019
014:12:49:38
150,05112
65.10
49.48
33.85
-014:08:46:36
40.95586
-014:09:05:16
55.62411
15% step change in accum
default for bad signal - to be confirmed verified by FOD.
33.33
8.33
-16.67
-014:10:25:20
-11.25000
1333.33
333.33
-666.67
014:09:28:00
-250.00000
014:09:10:00
523.22729
014:12:52:00
-433.33333
9:45
ETCS Pump off
10:18
Vent to radiator
GMT
2015_014:08:00:00
2015_014:09:40:00
2015_014:11:20:00
2015_014:13:00:00
The data source, "Archive File: MSTR.15.001.00.00", was opened

Normal Operating Conditions

EATCS Loop B



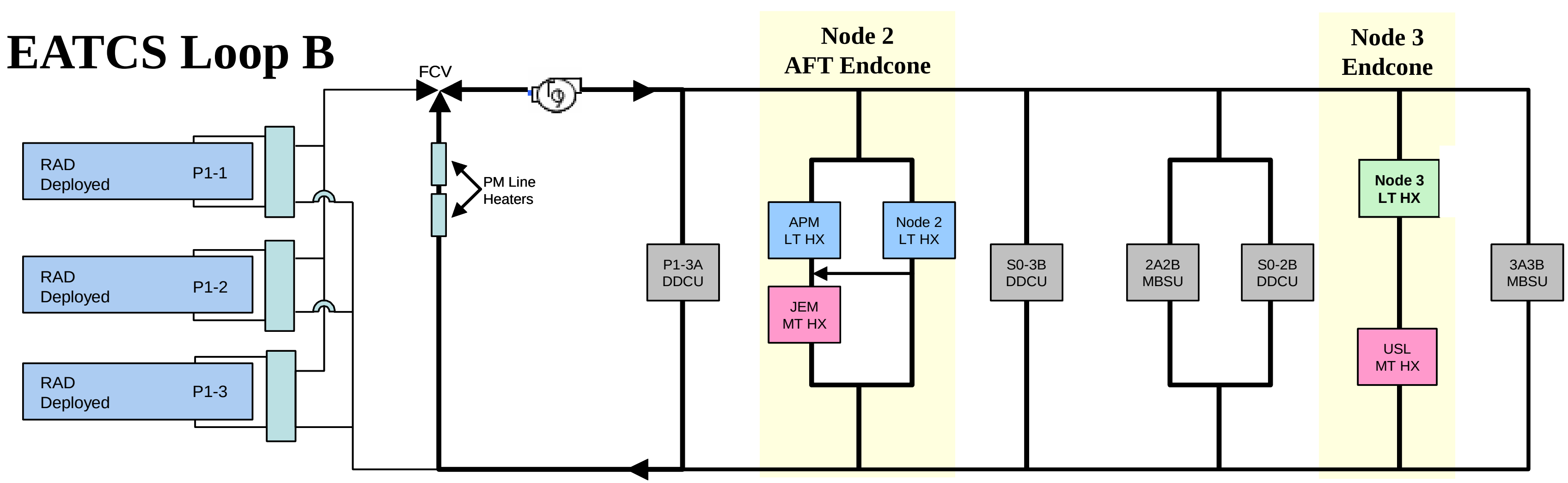
~13°C (56°F)
to very low temperatures

~13°C (56°F)

ITCS water temperatures are even warmer

Starting Conditions for Refill

- Node 3 LT HX was flowing and was warm
- Node 2 LT HX was flowing
- JEM MT HX was flowing
- APM LT HX was isolated and its heaters were on

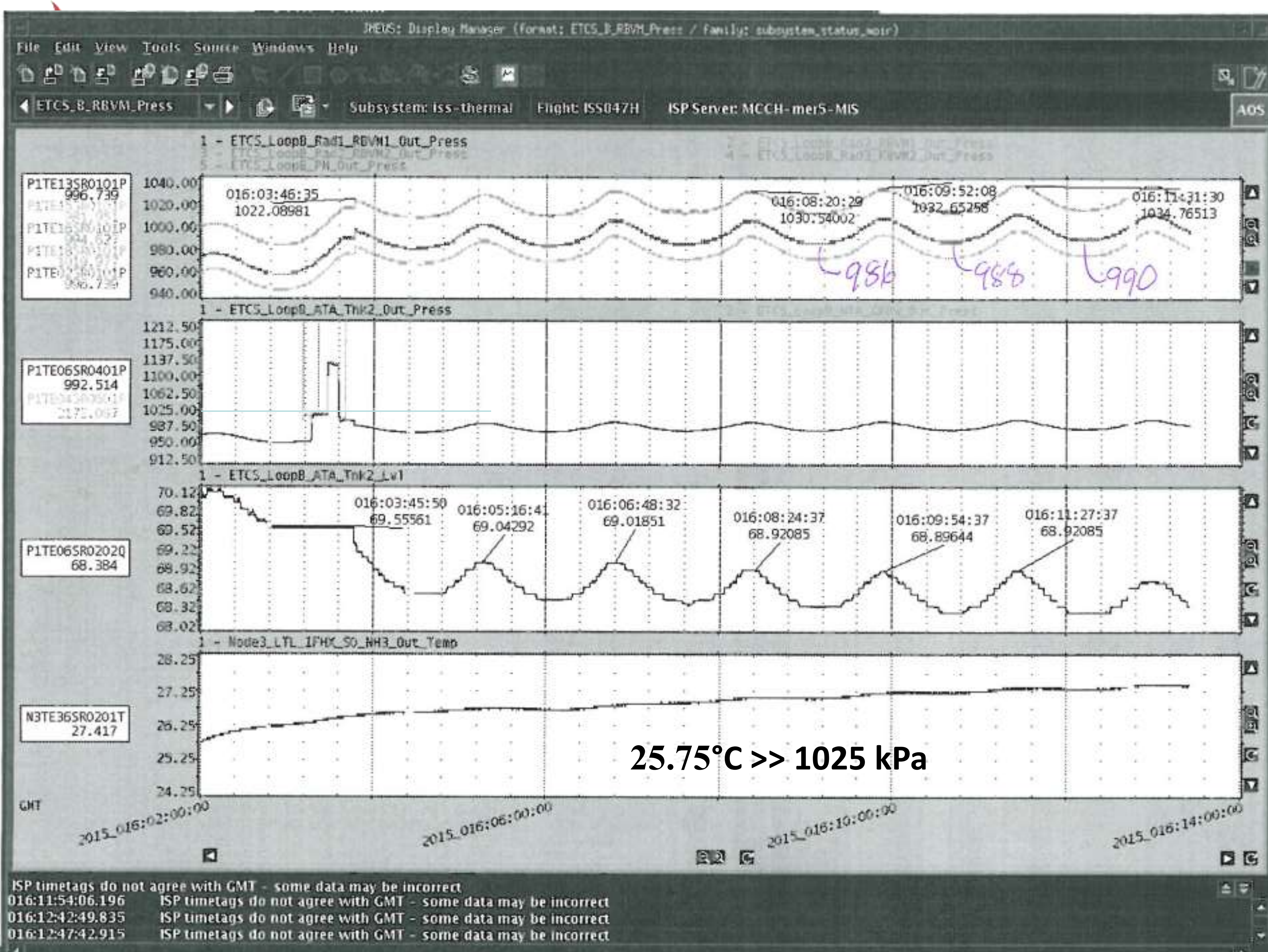


How Did We Know That There Was No Leak?

- Accumulator spike was not right
  - instantaneous accumulator level change is indicative of a large leak
  - a large leak would have stroked the accumulator fully
    - $p_{ATCS} >> p_{ITCS}$
- There was no instantaneous change in loop pressure
  - changes in gas cap accumulator quantity always result in changes in loop pressure

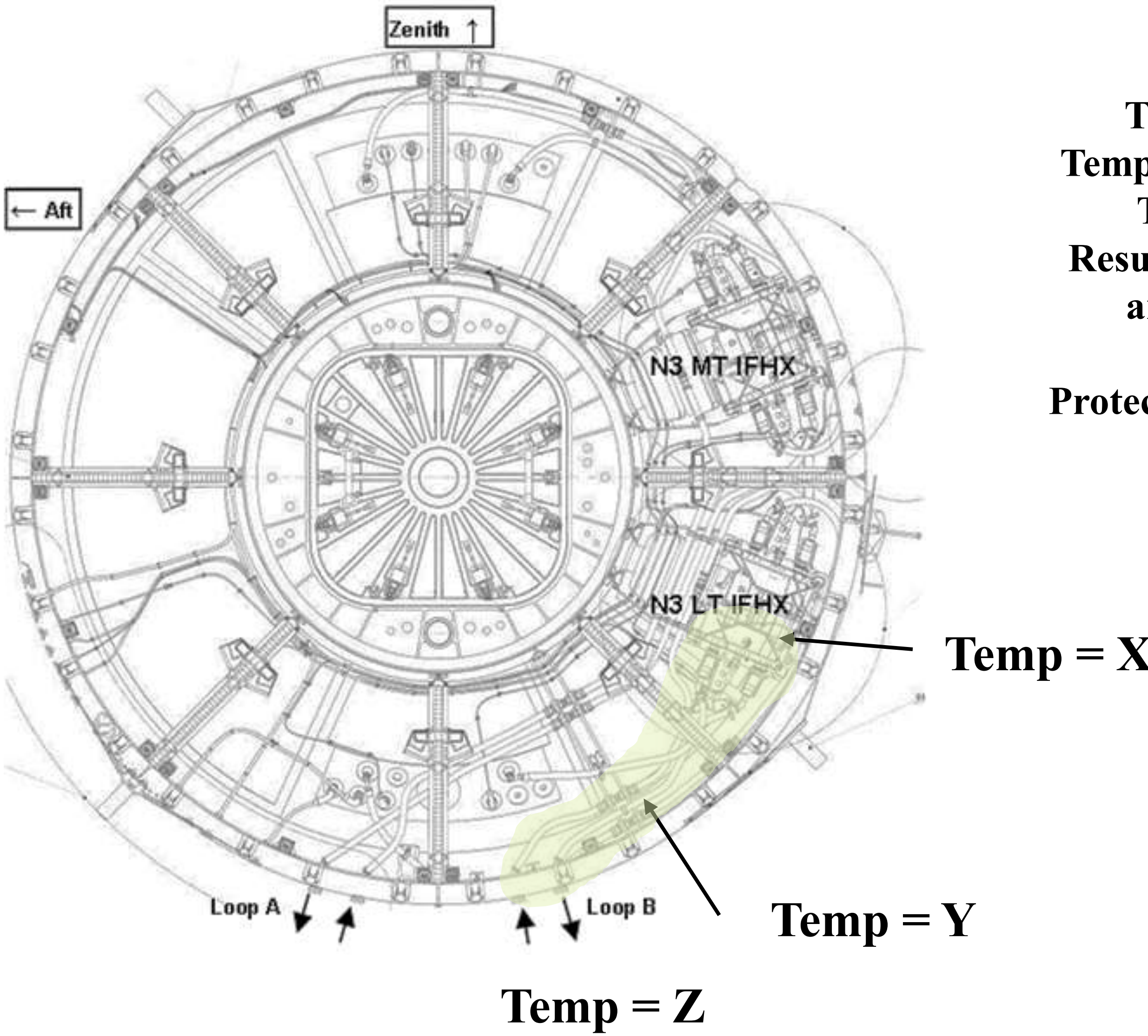
Initial Idea

- Since Node 3 LT was flowing and warm,
  - pressurize accumulator to a pressure below one that would force liquid into the Node 3 LT HX
  - observe the Node 2 endcone volume limit of 2.8 liters (0.1 ft^3)
  - wait for required dwell time
  - repeat
- One successful push was obtained but it was clear that we would soon run out of pressure headroom
  - as we pushed more liquid into the system, the liquid/vapor interface would be forced into warmer areas, creating higher pressures
  - Node 3 LT-induced saturation pressure limit would be reached



25.75°C >> 1025 kPa

Node 3 Endcone and Heat Exchangers



For Node 3:
Temp X ~ 26 C (telemetry)
Temp Y ~ 18-20 C (est. shell temp)
Temp Z ~ -29C (analysis)
Result: NH3 vapor in IFHX, cold ammonia not too far away

Protection of the Node 3 LTL IFHX was driving timeline

Pressure Increase Scenario

- Consider the loop pressure to be constant at 1000 kPa
- If the loop pressure is increased
  - Once p>1200 kPa condensation will occur
    - condensation can be limited by available heat transfer or vapor inflow
  - Once all vapor is condensed, liquid ammonia will be pulled into the heat exchanger core
    - 19:1 density ratio

contemporaneous chart

Pressure Increase Scenario

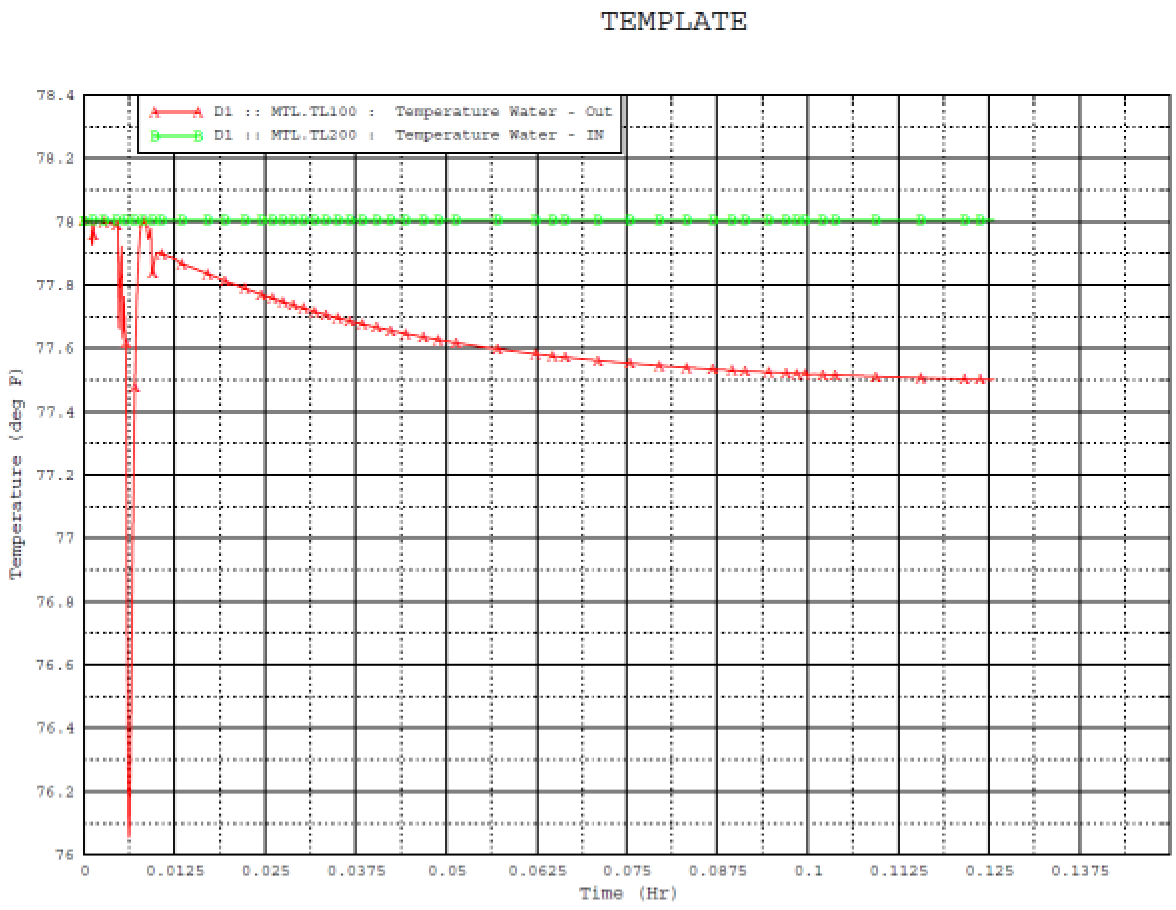
– Liquid inflow will be limited by the 0.032 inch orifice

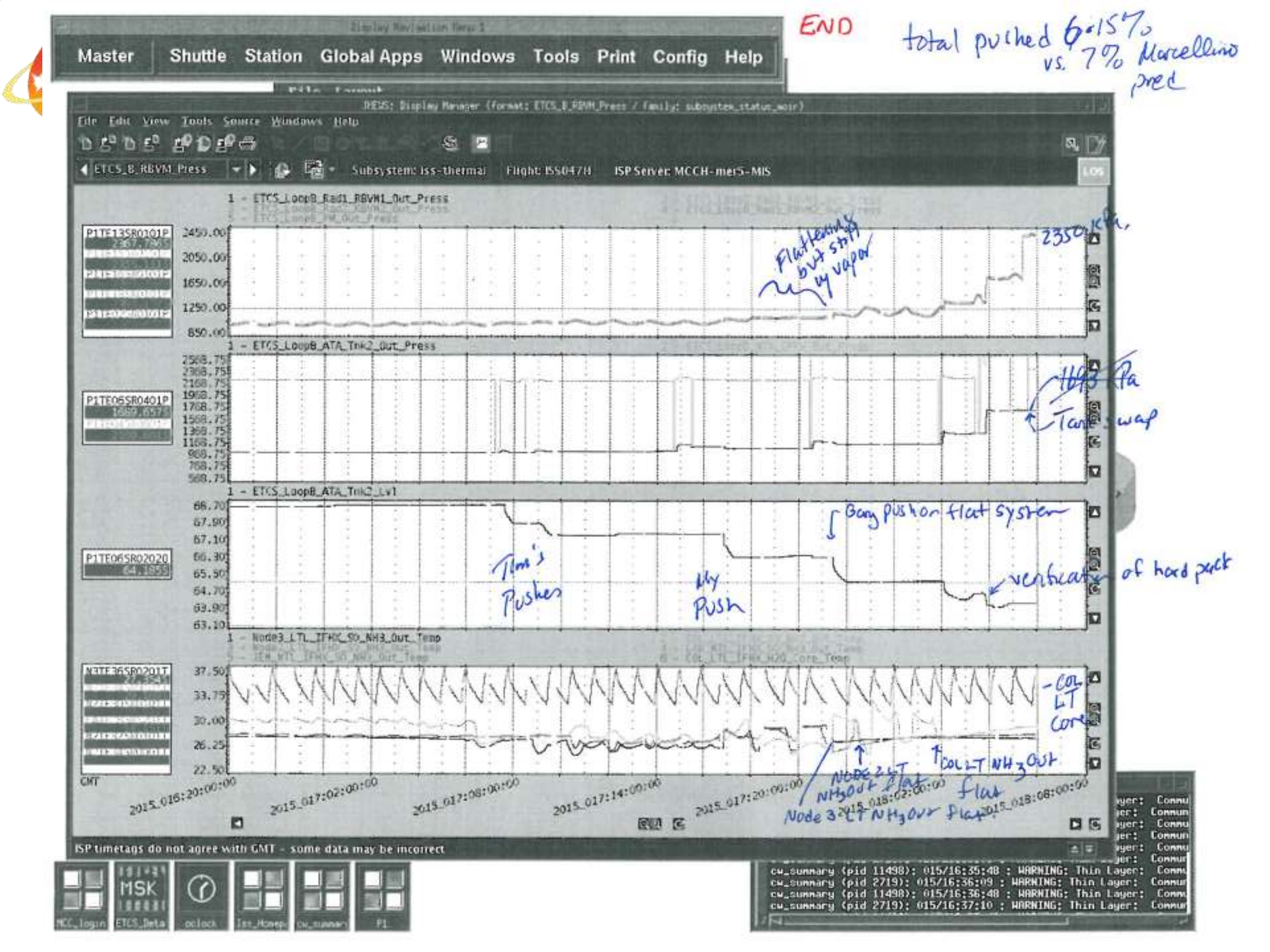
orifice Δp (psid)	orifice Δp (kPa)	m dot (lbm/hr)	minutes to fill core
1	6.9	7	9
5	34.5	16	4
10	69.0	23	3

orbital cycle Δ is ~45 kPa

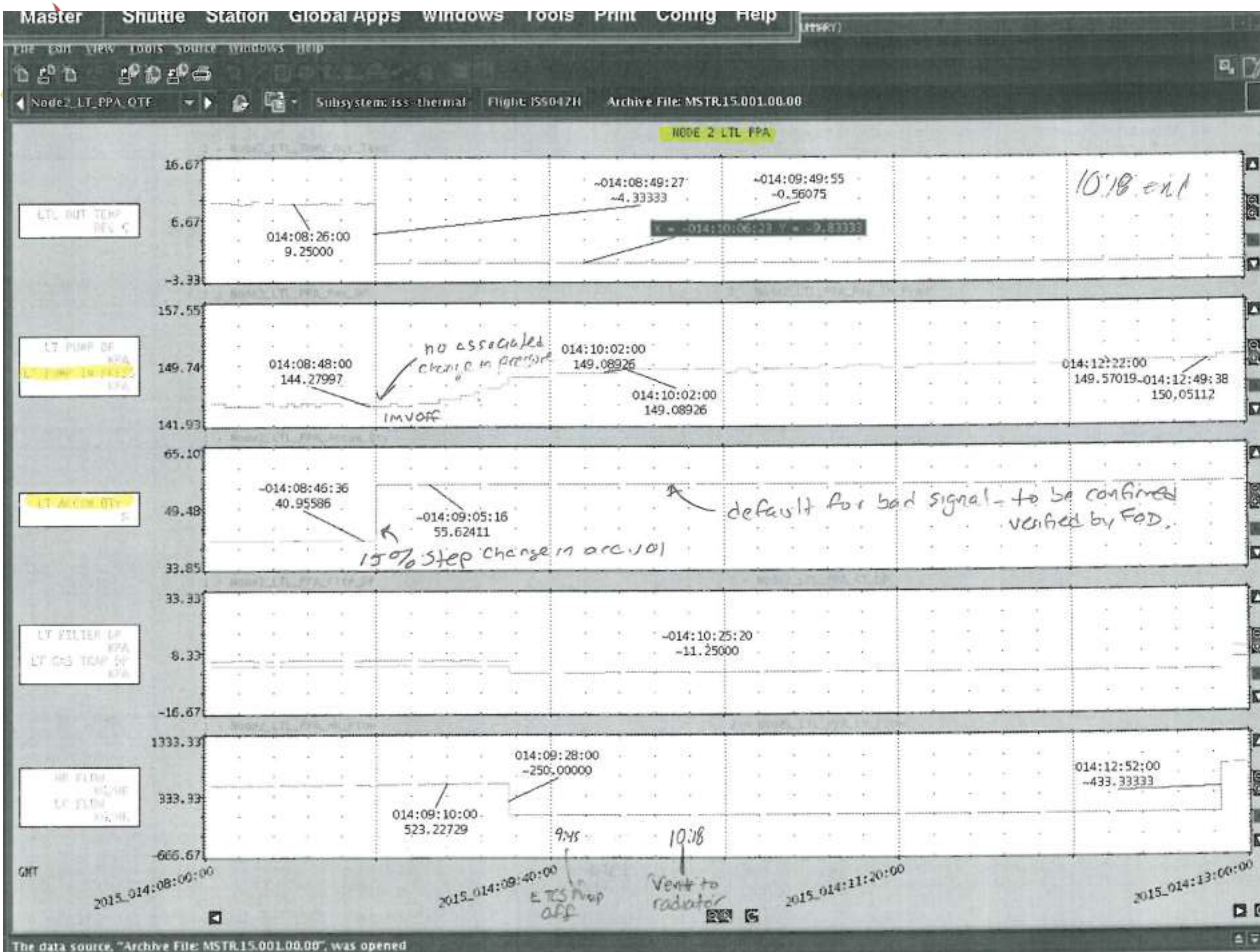
contemporaneous chart

Water Temperatures





END
total pushed 6.15% vs. 7% Marcellino pred
Master
Shuttle
Station
Global Apps
Windows
Tools
Print
Config
Help
File Edit View Tools Source Windows Help
ETCS_B_RBVM_Press
Subsystem: iss-thermal
Flight: ISS047H
ISP Server: MCCH-mer5-MIS
1 - ETCS_LoopB_Rad1_RBVM1_Out_Press
Flattening but still w/ vapor
2350 kPa
1 - ETCS_LoopB_ATA_Tnk2_Out_Press
~~1693~~ kPa
Tank swap
1 - ETCS_LoopB_ATA_Tnk2_Lvl
Bag push on flat system
Tim's Pushes
My Push
verification of hard pack
1 - Node3_LTL_IFHX_SO_NH3_Out_Temp
- COL LT Core
Node 2 LT NH3 Out flat
COL LT NH3 Out flat
Node 3 LT NH3 Out flat
2015_016:20:00:00
2015_017:02:00:00
2015_017:08:00:00
2015_017:14:00:00
2015_017:20:00:00
2015_018:02:00:00
2015_018:08:00:00
ISP timetags do not agree with GMT - some data may be incorrect
MSK


Master
Shuttle
Station
Global Apps
Windows
Tools
Print
Config
Help
Node2_LT_PPA_QTF
Subsystem: iss-thermal
Flight: ISS042H
Archive File: MSTR.15.001.00.00
NODE 2 LTL PPA
16.67
6.67
-3.33
014:08:26:00
9.25000
-014:08:49:27
-4.33333
-014:09:49:55
-0.56075
10:18 end
157.55
149.74
141.93
014:08:48:00
144.27997
no associated change in pressure
IMV off
014:10:02:00
149.08926
014:10:02:00
149.08926
014:12:22:00
149.57019
014:12:49:38
150.05112
65.10
49.48
33.85
-014:08:46:36
40.95586
-014:09:05:16
55.62411
15% step change in accum vol
default for bad signal - to be confirmed verified by FOD.
33.33
8.33
-16.67
-014:10:25:20
-11.25000
1333.33
333.33
-666.67
014:09:10:00
523.22729
014:09:28:00
-250.00000
014:12:52:00
-433.33333
9:45
ETCS Pump off
10:18
Vent to radiator
GMT
2015_014:08:00:00
2015_014:09:40:00
2015_014:11:20:00
2015_014:13:00:00
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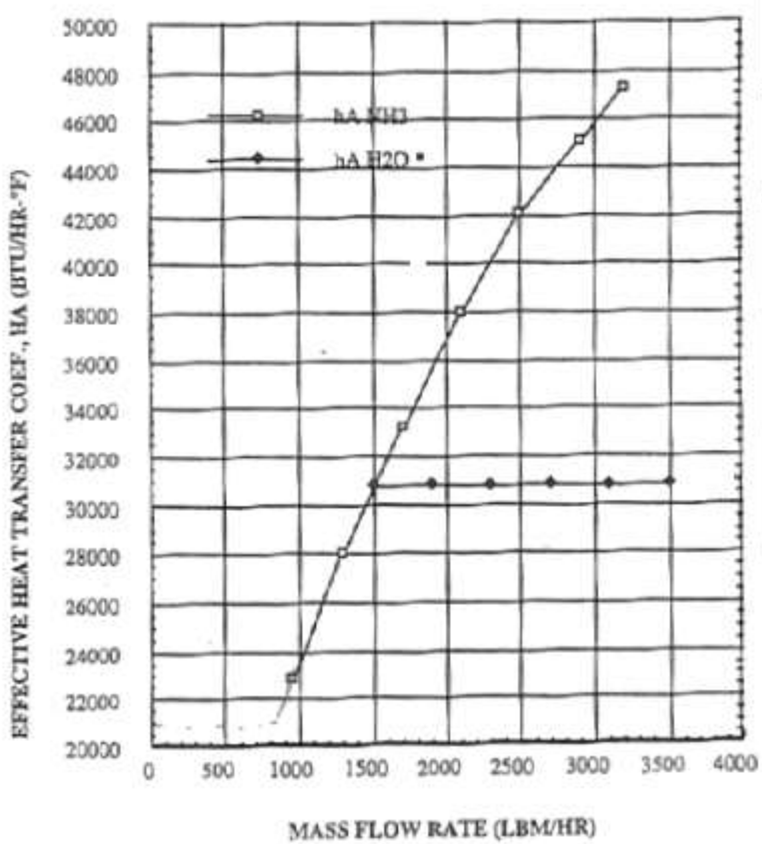
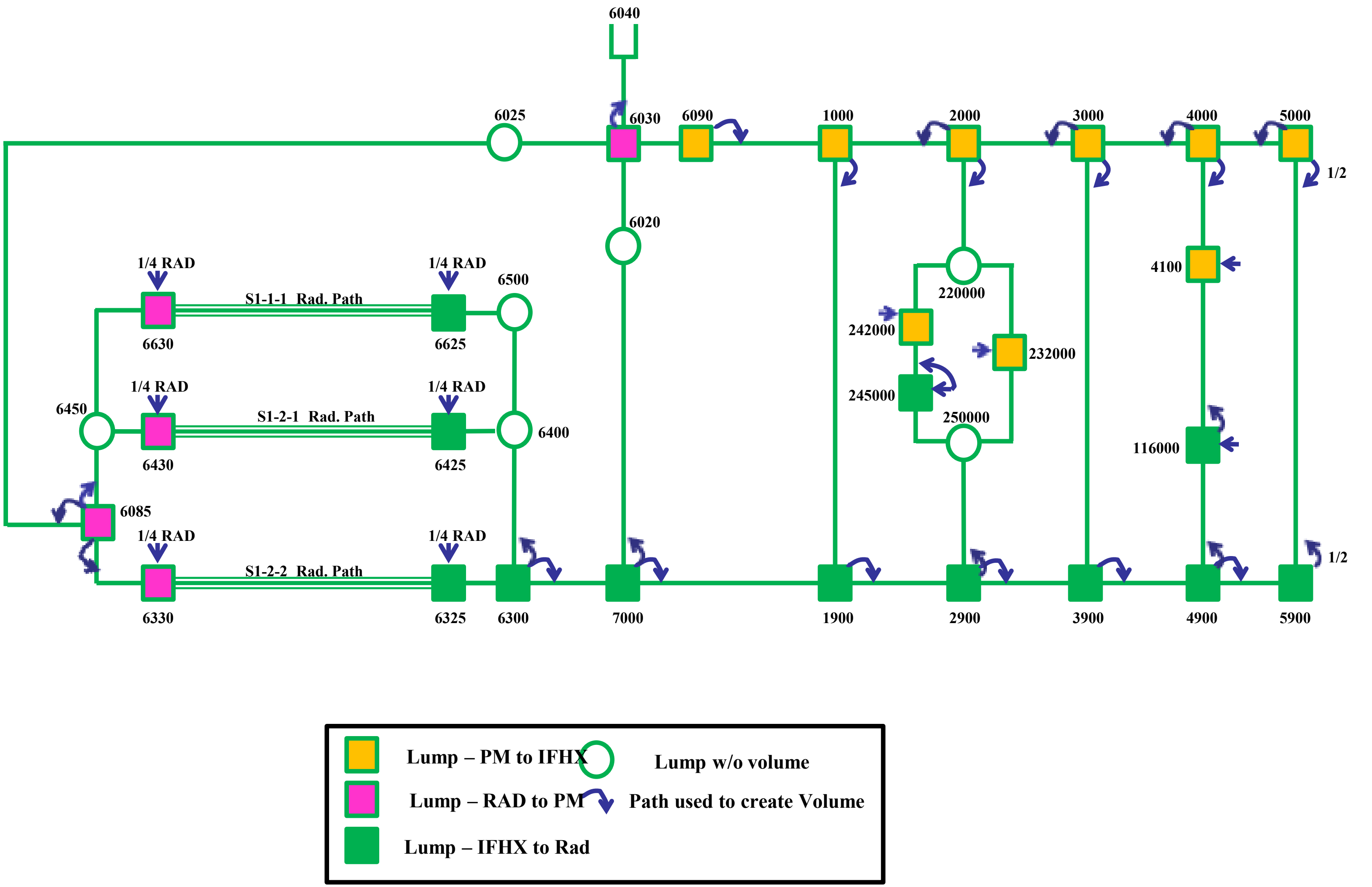
Heat Exchanger Performance

- water values used directly from vendor data
- ammonia values developed from basic principles
  - pure laminar flow does not allow for UA enhancement from serpentine nature of flow path

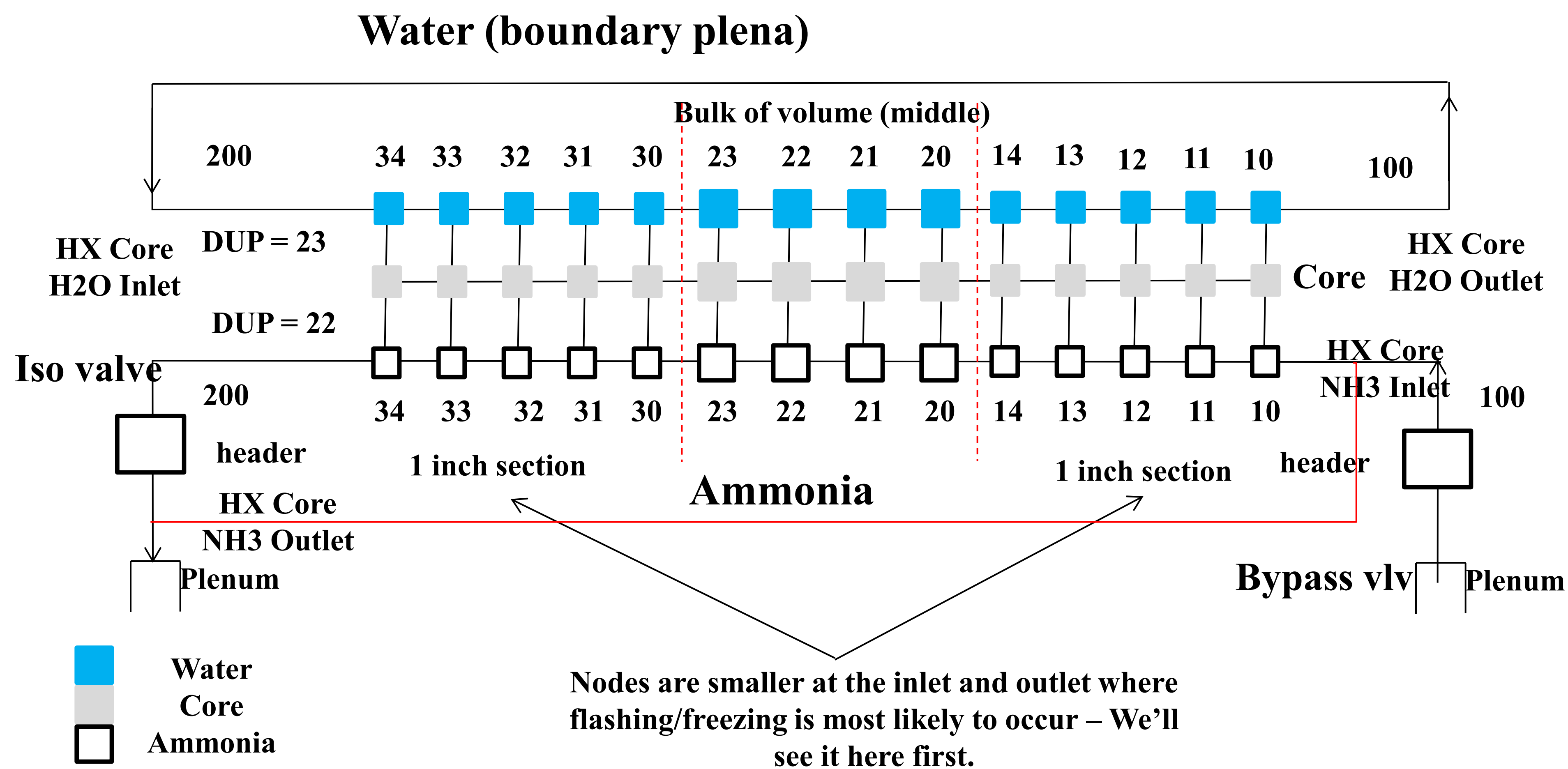


* Minimum Nussert number operation
hA = constant over given flow range

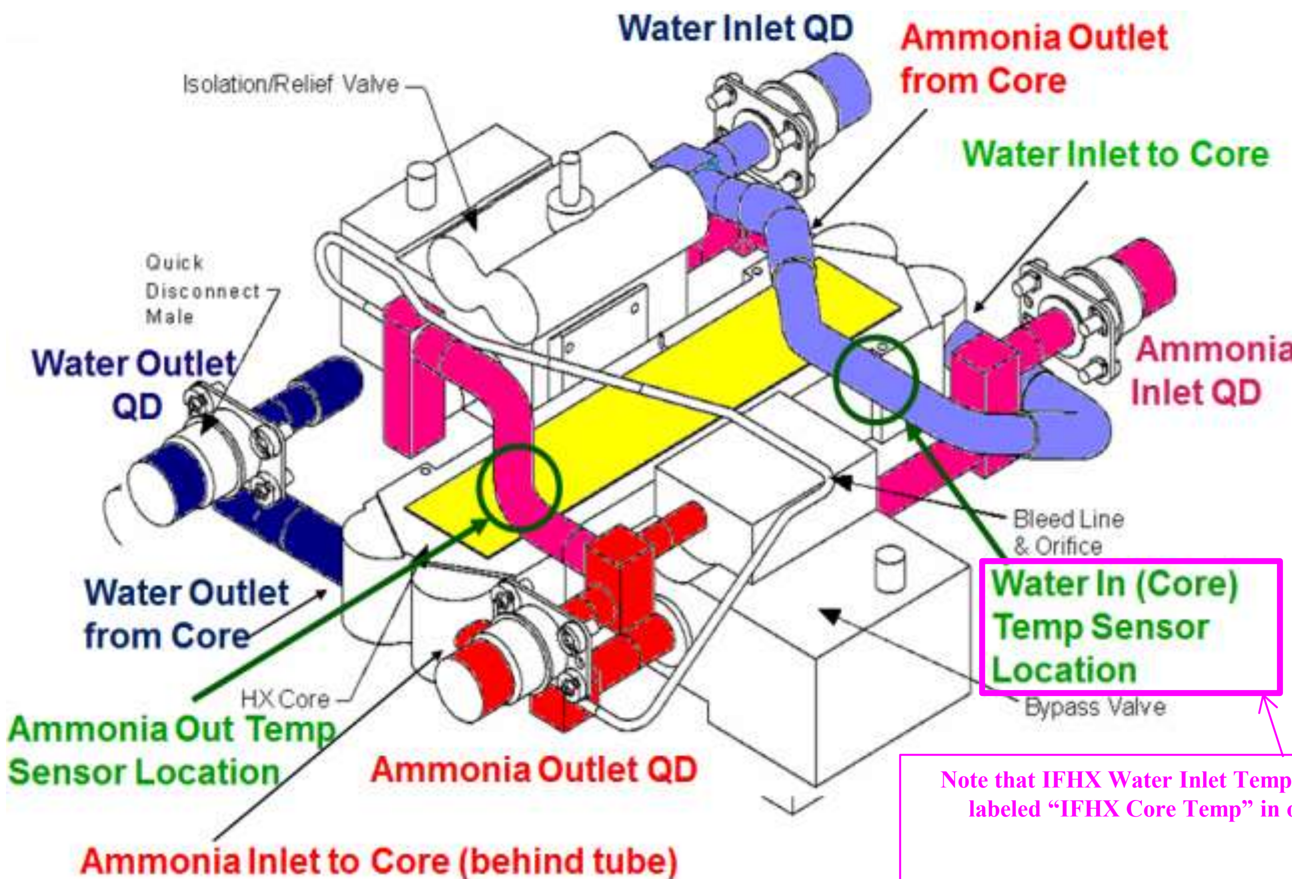
Simplified Model Schematic



Flowing IFHX Model Schematic
Normal operation



IFHX



Note that IFHX Water Inlet Temp Sensor is labeled "IFHX Core Temp" in op nom

Loop Configurations